HipGuard: A Wearable Measurement System for Patients Recovering from a Hip Operation

Pekka Iso-Ketola, Tapio Karinsalo, and Jukka Vanhala

Institute of Electronics, Kankaanpää Unit

Tampere University of Technology

Kankaanpää, Finland

Abstract—**This paper presents a wearable measurement system for patients recovering from a hip replacement operation. The system, called HipGuard, is intended to be used at home during the recovery period of eight to 12 weeks after the surgery. The system measures the posture of the patient and also monitors the load put on the operated leg. These measurements help the patient to follow the precautions given by the surgeon. The measurement system consists of seven wireless posture sensor nodes for measuring the orientation of the hip and the legs, and a wireless load sensor node for measuring the load put on the operated leg. The patient is informed by the HipGuard system with an audio signal or a haptic vibration if the position of the operated hip or the load put on the operated hip approaches set limits.**

Keywords-flexible electronics; hip replacement; posture measurement; wearable technology; wireless sensor network

I. INTRODUCTION

The number of hip replacement surgeries performed each year is continuously increasing [1]. To a large degree this is due to the continuously extending life expectancy and hence an increasing number of elderly population. Hip surgeries such as total hip arthroplasty or hemiarthroplasty, where a part of the hip bone (acetabular side) or the upper thighbone (femoral side) is replaced, require the surgeon to open the hip joint capsule. This weakens the structure of the hip and gives rise to a risk of dislocating the hip after surgery. On the basis of the type of surgery, the type of prosthesis and the general condition of the operated hip, the surgeon defines motion limits that the patient must follow during the recovery period of normal duration from two to three months before the first control visit to hospital.

The precautions vary for different types of hip surgeries [2]. When the hip joint capsule is opened from the front (anterior approach), the main positions and movements that the patient should avoid during recovery are bending the hip back, turning the hip and leg out, or spreading the operated leg outward. In the other approach, the hip joint capsule is opened from the back (posterior approach), and the patient should avoid bending the hip more than 90 degrees, crossing legs, or turning the hip and leg inward [2]. Following the given precautions helps the patient to prevent hip dislocation, which is one of the primary complications following hip replacement surgery.

Another part of the healing process is gaining muscle strength to the operated hip. A certain amount of weight should be put on the operated leg while doing exercises and daily routines, but excess load can cause damage to the operated hip especially during the recovery period. To prevent complications, the surgeon can give a limit for the load that can be put on the operated leg. This limit is usually in the range of 20 kg (44 lbs) during the first weeks of recovery and gradually rising as the recovery goes forward.

The length of stay at the hospital has declined substantially from the approximately ten days of early 1990s [3, 4]. The patient is nowadays in hospital care usually for five to seven days after the surgery, depending on the complexity of the operation [3, 5]. During this period a physical therapist will instruct the patient about the hip precautions, but once the patient is home it is up to the patient to follow the rules. The rules can be found much more difficult to follow in a domestic environment than they were in an unfamiliar environment like the hospital. Many daily routines, including sitting on a coach or a toilet seat, or picking up items from the floor, have the potential to cause dislocation of the operated hip.

Although it is estimated that less than 10 % of all hip replacement patients will need an additional hip surgery during their lifetime, the resources used for these hip revision surgeries and follow up care are immense, not to mention the distress and pain suffered by the patients [1, 4, 5]. In a study by Bozic et al. the mean total hospital cost of hip revision procedures was found to be up to 30 % higher than the mean cost of primary hip operations [5]. The prolonged operative times, increased risk of complications and longer length of the hospital stay are the main factors in the high costs of hip revision operations [4, 5].

The rationalization of the hip operation process, from diagnosis to follow-up care, has been widely studied [3, 6]. The efficiency gained in the procedures preceding the discharge of the patient plays an important role in reducing the total costs of hip replacement operations [3, 6]. On the other hand, the costs caused by complications occurring outside the hospital are much harder to control.

The prevention of dislocations and also the enhancement in home-based rehabilitation of the operated hip can be considered key issues in reducing the number of expensive

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revision surgeries. To address this problem we have designed a wearable measurement system for hip replacement patients, called “HipGuard”. The system is based on a garment integrated wireless sensor network and includes both motion limit and weight limit measurements for the operated hip.

II. System Architecture

The HipGuard system comprises of a pair of pants with seven wireless sensor nodes for unambiguous posture measurement of the operated hip, and an insole with a wireless load sensor node to measure the load placed on the operated leg. In addition to sensor nodes the HipGuard pants includes a central control and processing unit, which collects and processes the data from the sensor nodes and informs the user if the position of the operated hip or the load put on the operated leg approaches set limits. The control unit can alert the user by an audio signal (peep) or a haptic vibration, or by both of these means according to the user’s choice. The central unit can also relay the measured data and the issued warnings to a mobile device or a PC via Bluetooth connection, and to a wrist-top computer via ANT radio connection. The configuration of the HipGuard system is illustrated in Fig. 1.

Figure 1. Garment-integrated measurement system for hip replacement patients, consisting of a wireless sensor network for posture measurement, a wireless load sensor in the insole (footbed) and a central control and processing unit placed in the waist area. The user interface is provided by a wireless connection to a wrist-top computer and a mobile device. The sensors are connected to the control unit by ANT wireless personal network, which is also utilized by the wrist unit. Bluetooth link provides a wireless connection to a mobile device or a PC.

The posture sensor nodes are integrated into the pants in order for the measurements to correspond as well as possible to the actual posture of the hip. In an ideal case the sensor nodes would be fixed to the skeleton, which is only possible with implanted sensors. With a wearable system the best solution is to make a garment which conforms to the shape of the body and stays stationary on the surface of the skin. Even with this kind of sensor system the measurement results do not represent the actual position of the hip bone and the thigh bone as the movement of muscles and joints between the skin and the skeleton produce inaccuracy to measurements [7]. This inaccuracy can be reduced by an excess number of sensor nodes, placed around the measured limb, to provide redundant data for the calculations. For the presented application of monitoring the posture of a hip replacement patient these inaccuracies caused by the measurement set-up were considered small enough to be acceptable.

A. *Integration of the Sensor Nodes to the Garment*

The HipGuard system can be integrated into a pair of close-fitting pants or alternatively a construction of straps which are placed around the waist and legs. The latter approach allows the patient to use personal underwear but causes a problem with correct placement of the sensors and is likely to be less user-friendly to slip into than a pair of pants. The prototype of the HipGuard pants includes seven sensor nodes for posture measurement, one located on the side of the waist, one on both thighs, one on both shins, and one on both feet.

The integration of the sensor nodes to the garment is achieved by placing the electronics on top of the fabric and casting them into soft polyurethane. The process forms a flexible textile-integrated casing for the sensor nodes, which brings a notable advantage to regular solid casing in terms of wearing comfort and visual appearance. In addition to being a factor of comfort and aesthetics, the polyurethane casing provides mechanical and chemical protection to the electronics. The use of polymer-cast casing enables the electronics to be machine washable, which is an important feature for a garment-integrated wearable measurement system that should be used almost 24 hours a day.

B. *Wireless Sensor Network Communication*

The communication in the system is wireless. The control and processing unit is the central node in communication and also the configuration of the system is done through the control unit. For example a physical therapist can set the limits for hip position and load put on the leg by using a mobile device or a PC with a Bluetooth connection. The control unit receives data from the sensor nodes wirelessly via ANT radio link. The sensor nodes send the data to the control unit in predefined intervals which can be shortened when the posture or the load measurement comes close to the set limits.

The load sensor node in the insole works independently from the other sensor nodes and therefore the calculation of the load can be made in the sensor node. This enables the sensor node to know when the set weight limit is approaching and when the data should be send to the control unit. The calculation of the posture of the operated hip requires data from all posture sensing nodes, and therefore the data sending interval can not be decided by the individual sensor nodes. To adequately sense the changes in the user’s posture, a measurement interval with a sample rate of 40 Hz has been applied. This is always a compromise between the amount of data transfer and the accuracy of the results. Each posture sensor node calculates its own orientation, resulting in two angle values, one represent the angle in horizontal plane and the other the angle in vertical plane. This reduces the amount of transmitted data as the individual values of the three axes of the accelerometer and the two axes of the magnetic sensors don't need to be sent to the control unit. Another option would be to do all the calculations in the control unit. In this option the increase in data transfer is accompanied by the possibility to use simplified sensor nodes that only send the data to the control unit without analyzing it first.

III. SYSTEM MODULES

A. *Central Control and Processing Unit*

The central control and processing unit handles all the sensor data and communication between different parts of the system. The garment integrated and wearable components of the HipGuard system, which include the control unit, the sensor nodes and the wrist unit, form a Body area network (BAN) that utilizes a short range ANT radio network. Additional peripherals such as mobile devices and PCs are connected to the system by a Personal area network (PAN) that utilizes Bluetooth radio link. The control unit operates as a communication hub between the ANT protocol and the Bluetooth protocol providing fluent data transfer between BAN and PAN. Connection via mobile phone enables data from the HipGuard system to be transferred for example to a personal Internet log or a hospital information system.

B. *Posture sensor nodes*

The posture sensor nodes measure the orientation of the patient's waist and legs in order to provide sufficient amount of information to unambiguously calculate the posture of the hip. The orientation measurements can be done by accelerometers, magnetic sensors and gyroscopes [8], [9], or the relative angles of the joints can be measured with mechanical sensors and elongation gauges [10]. The problem with elongation measurements in garments is that each joint should have multiple elongation gauges to provide information in all directions including rotating movement of the joints. This was regarded as an overly complicated solution for the given application, and was therefore dismissed.

In a wearable application the wireless sensor nodes should be as small as possible and have low power consumption. The number of sensor components used in each node mediates to the power consumption, the required calculation power and the size of the node. The wireless data transfer also sets restrictions to the sample rate of the measurements as the power consumption increases when the measurement interval gets shorter. With the HipGuard system it was considered that a simple measurement system, which could perform most of the calculations at the sensor nodes, should be preferred even at the expense of reduced dynamic response. For this task accelerometers and magnetic sensors were chosen. Excluding the gyroscopes makes the nodes smaller and reduces the power consumption. Also the possibility to improve the dynamic response of the measurement, associated with gyroscopes, was not considered crucial for this rehabilitation application. With a sport activity monitoring application the preference could be quite different.

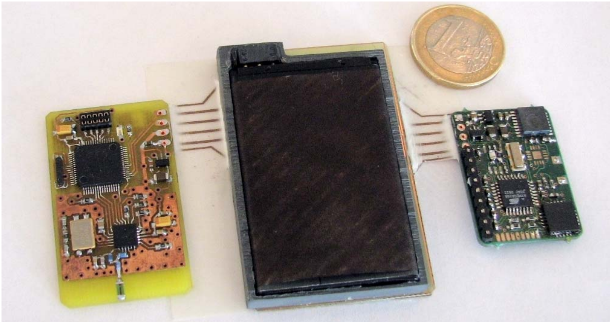

Figure 2. Electronics of the posture sensor node. The sensor node includes an ANT radio tranceiver (left), a battery (middle) and a sensor circuit board (right).

With accelerometers the orientation can be defined by measuring the direction of the field of gravity when the movement is static. This orientation is not however unambiguous in a horizontal plane and other sensors must be added to complement the measurements. The biggest issue concerning orientation sensing with accelerometers is the fact that they sense the acceleration caused by the movement of the subject, which must be taken into account in the filtering of the signal and in the final calculations.

Magnetic sensors are used in the system to measure the magnetic field of the earth. Similarly to the accelerometers, the orientation sensed by the magnetic sensor is not unambiguous in all planes. However as the direction of the field of gravity and the direction of the magnetic field of the earth differ from each other, with the exception of circumpolar areas, the combined results of the measurements can be used to calculate an unambiguous orientation of the sensor nodes. The posture sensor nodes in the HipGuard system include a 3-D accelerometer and a 2-D magnetic sensor. While the 2-D magnetic sensor is adequate to define the horizontal orientation of the sensor node, the third axis of the magnetic sensor could be used to improve the sensitivity of the measurement when the sensor is tilted. In addition to sensors the node includes a battery and an ANT radio transceiver. The electronics of the posture sensor node is presented in Fig. 2.

C. *Load Sensor Node*

The load sensor node placed in the insole of a shoe measures the load the patient puts on the leg that is on the operated side. This load is related, but not directly proportional, to the force that is directed to the hip joint. The measurement result is used to give strain information to the user of the HipGuard system. This information is important during the rehabilitation period, as the operated hip should be strained within certain limits, but not overstrained to prevent damaging the healing hip. The current rehabilitation procedure deals with weight limits, set by the surgeon, for the load put on the operated leg. To enable the use of the same limits with the HipGuard system, the force values must be scaled to kilograms.

The sensor type chosen for this task was a capacitive sensor in the form of a capacitor with a self-restoring collapsible insulator material. Capacitive sensor is advantageous due to its capability to measure static forces and the possibility to manufacture thin sensors that cover a large area. The force directed to the sensor can be measured as a change in capacitance caused by the change in insulator thickness.

To measure the whole force that is directed to the foot, the whole area of the foot should be covered with sensors. This kind of system would be difficult to implement and instead the measurement is made from two selected areas under the heel and the ball of the foot. Combining the measurement results of these two areas gives an estimation of the total force directed to the leg. The data values are transferred wirelessly to the control unit, which gives the user an audible or haptic feedback when set limits are approached. The load put on the operated leg can be measured with accuracy in the range of 1 kg, which can be considered adequate for this application.

IV. SYSTEM OPERATION

The HipGuard system is designed to be as easy to use as possible for the patient. Once the posture and weight limits are set by the doctor or the physical therapist, the user only needs to turn on the system from the control unit and the system is ready to be used. The measurement starts by a reference measurement, where the user stands still at attention for 10 seconds. The values received from this measurement represent the reference angles of the joints. After the reference measurements, the orientation of each sensor node at any given moment is calculated by comparing the data to its own reference value. This way there will be no drifting of values during the measurement.

The angles of the joints are calculated by comparing the values of different sensor nodes. The waist sensor node defines the orientation of the user's hip. To calculate the angle between the upper body and the thigh, the orientation of the thigh sensor node is compared to the orientation of the waist sensor node. Similarly to calculate the angle of the knee, the orientation of the shin sensor node is compared to the orientation of the thigh sensor node. The knee angle has no direct impact to the hip, but it can be used to help the interpretation of the rotation of the leg, which would be difficult to measure just by the thigh sensor unit. Another additional measurement, and also the most straightforward measurement, for interpreting the leg rotation is the rotation angle of the foot sensor node compared to the waist sensor node. These measurements, together with the load measurement from the insole, provide all the information needed to monitor the precautions set for the patient recovering from a hip operation.

V. CONCLUSION AND FUTURE WORK

In this paper, a wearable measurement system for patients recovering from a hip operation has been presented. The need for such system comes from the relatively long rehabilitation time that the patient spends home. To prevent the dislocation of the operated hip, the patient needs to follow strict precautions during the recovery period.

The HipGuard system allows the patients to exercise and move more freely than they normally would as the system gives an alarm whenever the movement limits set by the surgeon are approached. The system provides a wireless sensor network with accelerometers and magnetic sensors capable of measuring the posture of the user's waist and legs. The system also measures the load put on the operated leg with a capacitive sensor specially designed for this application. The wireless communication between the sensor nodes and the control unit is realized by ANT radio network, and the connection to outside systems is made possible through a Bluetooth link. The connection to mobile devices enables the data to be mediated to an outside service e.g. an Internet log or a hospital information system.

The integration of the sensor nodes to the garment makes the system unobtrusive and comfortable to wear. The polyurethane-cast electronics is machine washable, which makes long-term use of the system possible without the need to remove the measurement electronics from the garment.

The constructed HipGuard prototype is intended to be tested in a rehabilitation hospital in the near future. This way the patient can be instructed on the use of the HipGuard system by a physical therapist during the rehabilitation period at the hospital, after which the patient will take the HipGuard system home and continue the rehabilitation of the operated hip independently. The results of these user tests will show the true applicability of the system.

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